# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM

No. 1087

## STRENGTH INVESTIGATIONS IN AIRCRAFT CONSTRUCTION UNDER REPEATED APPLICATION OF THE LOAD

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Luftwissen
Vol. 6, No. 2, February 1939

Reprint of R.T.P. Translation No. 1415
Issued by the Ministry of Aircraft Production,
London, England



Washington
August 1946

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# STRENGTH INVESTIGATIONS IN AIRCRAFT CONSTRUCTION UNDER REPEATED APPLICATION OF THE LOAD[1]

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In the calculation of the dimensions of modern machines and building constructions, account is taken of the frequency of the occurrence of the anticipated loads. It is generally assumed that these loads will be repeated an infinite number, or at any rate some millions, of times during the total working life of the construction. When calculating the dimensions of the structural parts of aircraft, on the contrary, a consideration only of those frequencies in the appearance of the loads which actually come into play in the various states of stress is allowable. This is because in aircraft construction it is absolutely essential not only to ensure adequate structural strength but also to keep down the structural weight to the lowest possible limit. Strength tests in which this requirement is directly taken into account have recently been carried out by the DVL Material Strength Department.

## STRESSES OCCURRING IN FLYING OPERATION

The stresses produced in an aircraft fluctuate in varying measure, according to the nature and purpose of the machine, about a mean load, which corresponds to the air forces in unaccelerated horizontal flight, hence to the value of the total loaded weight of the aircraft multiplied by unity. These load fluctuations or "load multiples" do not succeed each other in obedience to any definite law. They are produced by gusts of varying strength and direction and as the results of the operation of the controls. Large fluctuations occur considerably less frequently than smaller ones (more details may be found in references 1 to 5.)

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[1]"Festigkeitsversuche mit wiederholter Beanspruchung im Flugzeugbau." Luftwissen, vol. 6, no. 2, Feb. 1939, pp. 61-64.

Extensive statistical investigations by the DVL Flight Mechanics Institute have recently provided reliable numerical data concerning the frequency of the occurrence of these stresses. (For details, see reference 5.) Figure 1 shows, for example, the result of such stress measurements represented as a "sum curve." The ordinates in the diagram are numbered according to fractions or multiples of a load amplitude denoted by "1." The abscissas show how often the individual load "steps" are exceeded within a prescribed operational time or flying distance. In order to get an idea of the actual conditions from the diagram, a scale should be applied to the ordinates, such that the load step marked "1" gives the load applied when flying into a gust of 10 meters per second acting perpendicularly to the direction of flight ("gust load" = additional load due to gust). The frequencies plotted in figure 1 for the occurrence of loads exceeding the individual load steps then hold roughly for a transport airplane with a total service life of the order of 3000 hours with a total flying distance of the order of $1.05 \times 10^6$ kilometers at a speed of 350 kilometers per hour (European Continental air traffic).

According to Kaul (reference 5) positive and negative gusts occur with approximately the same frequency. The obvious procedure is, therefore, to count one positive and one negative gust load together as one "load alternation," although the two states of load certainly do not in reality follow each other immediately. The sum curve in figure 1, then gives both the number of the positive or negative gusts and also the number of the gust load alternations. Here, only the fluctuations of loads superimposed on the mean load are counted, and not the smaller fluctuations in the nature of harmonic oscillations otherwise produced.

## STRENGTH TESTS AS INTERPRETING FLIGHT STATISTICS

If a strength test on an aircraft component is to be directly adapted to the results of flight statistics, the succession of all high and low stresses occurring in flying operations, namely, in the most haphazard order, must be imposed in this test. An example of the course of a test of this kind is shown by figure 2. For technical reasons, the total load range is subdivided into 9 load steps and the whole series of loads into 12 load cycles. Each cycle in the example selected here comprises $0.9 \times 10^6$ gust load alternations (at 350 km/hr this number corresponds to about 250 flying hours). In order to obtain a mixture of high and

low load steps conforming more or less to service conditions, all the load steps contained within each cycle were run through once in the descending and once in the ascending direction. It remains to be seen whether perhaps some other cyclic range or some other sequence of the load steps may be more suitable.

Figure 3 shows the synoptic diagram of a "strength test as interpreting flight statistics" taking as an example a perforated duralumin tube (Flieg 3115). The "sum curve of the test", namely, the stepped line $k_2$, indicates, by the widths $\Delta H$ of its steps, the frequencies of the load repetitions which were run through altogether in the individual load steps during a test in accordance with figure 2. As may be seen, the test was so chosen that its sum curve very closely followed the given "sum curve" of the operational loads, namely, the line $k_1$. (Cf. fig. 1.) To be on the safe side, the sum curve $k_2$ was made to coincide with the curve $k_1$ in the region of the highest load steps.

Comparative tests showed that the part under test would have "just" still held out in accordance with the sum curve $k_2$ without failure; that is, on increasing the ordinate scale, fracture would have appeared already within the total specified frequency. It may be regarded as probable, that the part under test would also have just still satisfied the sum curve $k_1$. The curve $k_3$ further drawn in figure 3, is thus the sum curve of the operational loads which the part under test would have satisfied with the requirement of a standardized factor of safety 1.35 against all load peak values (peak value = mean load + load amplitude).

It is essential that, in such a "strength test as interpreting flight statistics," all load steps are applied repeatedly to one and the same part. In order to show clearly the difference between tests of this kind and the usual treatment in strength tests, a brief survey of different forms of testing is given below.

## OTHER TREATMENTS OF STRENGTH TESTS

Hitherto, the technique of tests applied to aircraft construction has been limited in the main to the single application of load, as is the usual practice in the "static strength test" in other branches of strength testing technique. In aircraft construction such static tests are intended to

show whether the specified factors of safety, in particular 1.8(sometimes also of smaller or larger value), as against the "safe loads" exist. (For details, see reference 6.) In machine and engine construction, generally, and in building construction at the present time, strength tests with repeated application of the load are given preference, when the individual part undergoing the test is subjected repeatedly to one and the same load amplitude till failure occurs. The terms "fatigue strength tests" or "endurance" strength tests are employed according to whether in such tests the repetitions of the load applications are of the order of $10^6$, or more, or whether fewer repetitions already lead to failure. (The results obtained from a number of similar test parts are represented graphically in the form of "Wöhler curves".) (Cf., for example, figs. 2 to 7, also reference 10.) These fatigue and endurance tests will be referred to as "one step repetition tests."

Neither static tests with a single application of load nor one-step repetition tests provide direct information as to whether and how long an aircraft part can withstand the continued application of high and low operational loads. For example, no rule can be given as to what number of repetitions of one or more selected load steps must be endured by the individual part under test, if the whole succession of load applications is to be covered.

The tests carried out by French (reference 7) and Müller-Stock (reference 8) and the studies of Langer (reference 9), Thum and Bautz (reference 10), Kloth and Stroppel (reference 11), constitute an approach toward the realization of the "strength tests as interpreting flight statistics."

French (reference 7) deals with the question as to how often a load step (step 1) above the fatigue strength can be withstood without the fatigue strength (step 2) of the part under test being reduced. The result of "two-step repetition tests" carried out for this purpose has been represented by French in the form of "probable damage lines." In these a frequency is coordinated with each stress value of step 1, on exceeding which the (permanent) fatigue strength of the part is reduced.

In the generalization of this conception, naturally, in place of fatigue strength (step 2) any other stress value may be used as the comparison step. The latter may also be selected higher than step 1. In this sense, Müller-Stock (reference 8) has carried out two-step repetition tests, which

go beyond those of French, since he not only determines the frequency of step 1 above, which a reduction of the otherwise tolerable frequency of a comparison step appears; but he has at the same time sought to establish how this reduction depends numerically on the frequency of step 1. In further tests, Müller-Stock deals also with the question as to the extent to which the tolerable frequency of a third step is influenced by a load that has been previously applied alternately in two steps with certain frequencies.

Direct conclusions cannot be drawn from the experimental work of French and Müller-Stock, as they stand, with regard to the problem as it affects aircraft construction, although certain relations must surely exist between the results of these two or three step repetition tests and the results of the tests as interpreting flight statistics. In view of this possibility, "damage lines" as interpreted by French were determined by the Material Strength Section of the DVL for a number of semifinished aircraft parts. As the results of these tests will be of general interest, the damage lines for tubes of Cr-Mo steel, duralumin, hydronalium, and electron are shown in figures 4 to 7. The stress values of these damage lines differ only from the corresponding values of the Wöhler curve.

Langer (reference 9) assigns certain assessment coefficients to the different load steps of a complete sequence of high and low loads according to the frequency with which they are attained within the individual load cycles. According to Langer, the load-carrying capacity of a structural part is exhausted when the sum of all assessment coefficients has reached a certain value. In this, account is taken of the fact that the very frequent application of loads below the fatigue strength may, in some circumstances, neutralize the detrimental effect of a few applications of loads above the fatigue strength. No account is taken, on the contrary, of the probability that the assessment coefficient of each load application cycle is greatly influenced by the cycles preceding and following it. The order in which the different load application cycles alternate will play a particularly important part in this connection.

Thum and Bautz (reference 10) seek to interpret a sequence of high and low loads by tests with repeated stress in one step only selected out of the whole load cycle, that is, by one-step repetition tests. Load steps above the one selected for the test are taken into consideration by increasing the frequency of the test load step to a valve above that which it reaches in reality. Such considerations, however, hold

only for the case where the test load step lies above the fatigue strength. As in Langer's work, here again the influence of all preceding and following load cycles on the assessment coefficient of each individual load cycle is neglected. Thum and Bautz still give no clear rules of any kind for the execution of the strength tests concerned nor for the determination of the dimensions of the structural part.

Kloth and Stroppel (reference 11) were the first to utilize the sum curve of the operational stresses for the assessment of the strength characteristics of land machine parts. They came to the conclusion, however, that, in view of the "interference stresses," the structural parts should be so dimensioned that their fatigue strength lies above all otherwise "normal operational stresses." (Such a rule for dimensioning would not be suitable in airplane construction.)

## CONCLUDING COMMENTS

As opposed to the otherwise usual utilization of strength tests, the recent tests of the Material Strength Section of the DVL are characterized by the fact that they are directly adaptable for the whole sequence of all loads occurring under operational conditions. Today, the usual methods of fatigue and endurance testing cannot in any way take the place of tests of this kind, that is, by making one- and two-step repetition tests. The results of such strength tests will probably show certain relationships with "Wöhler" and "damage" lines.

The tests now in progress at the DVL Material Strength Section are intended first to provide information on fundamental questions: for example, on the influence of the order of sequence and distribution of the individual load cycles within the total cycle, on the influence of pauses of rest, and so forth. So far as it is possible now to make any statements, it would appear as though a sequence of load application descending in monotone, beginning with the highest load would be considerably less favorable than, for example, a sequence as represented in figure 2. If the continuity of the load sequence is interrupted by relatively long pauses, it may be expected, according to trial tests carried out with duralumin (Flieg 3115) with a two-day interruption after each complete cycle, that there will be a reduction in the total tolerable frequency.

Translation by M. Flint.

## REFERENCES

General considerations on the stresses occurring in flying operation are contained in the following papers:

1. Hertel, Heinrich: Dynamic Breaking Tests of Airplane Parts. NACA TM No. 698, 1933. Die Verdrehsteifigkeit und Verdrehfestigkeit von Flugzeugbauteilen. Jahrb. 1931, DVL, pp. 165-220.

2. Teichmann, Alfred and Michael, F.: Safety and Design in Airplane Construction. NACA TM No. 755, 1934.

3. Küssner, Hans Georg: Häufigkeitsbetrachtungen zur Ermittlung der Erforderlichen Festigkeit von Flugzeugen. Luftfahrtforschung, vol. 12, no. 2, May 16, 1935, pp. 57-61. (Air Corps Trans. No. 308)

4. Neesen, Arthur and Teichmann, Alfred: Bemerkungen zu den Vorschriften für die Festigkeit von Flugzeugen. Luftwissen, vol. 2, no. 8, Jan. 1935, pp. 201-214 and vol. 2, no. 9, Sept. 1935, pp. 251-254.

Detailed statistical considerations on the load frequencies in operational flying are contained in:

5. Kaul, Hans W.: Statistical Analysis of the Time and Fatigue Strength of Aircraft Wing Structures. NACA TM No. 992, 1941.

Details on the present strength requirements of aircraft are to be found in:

6. Bauvorschriften für Flugzeuge, No. 1: Vorschriften für die Festigkeit von Flugzeugen. Edition Dec. 1936.

Recent strength tests in machine construction and materials are described in:

7. French, H. J.: Fatigue and the Hardening of Steels. Trans. Amer. Soc. Steel Treat., vol. 21, 1933, p. 899.

8. Müller-Stock: Der Einfluss dauernd und unterbrochen wirkender schwingender Überbeanspruchung auf die Entwicklung des Dauerbruchs. Mitt. Kohle- und Eisenforschung, vol. 2, no. 2, March 1938.

9. Langer, B. F.: Fatigue Failure from Stress Cycles of Varying Amplitude. Jour. of Appl. Mech., Trans. A.S.M.E., vol. 4, no. 4, Dec. 1937, pp. A-160-A-162.

10. Thum, A., and Bautz, W.: Zeitfestigkeit. ZVDI., vol. 81, 1937, p. 1407.

Statistical data on the load frequencies were employed for the first time in strength considerations in:

11. Kloth and Stroppl.: Kräfte, Beanspruchungen und Sicherheiten in den Landmaschinen. ZVDI., vol. 80, 1936, p. 85.

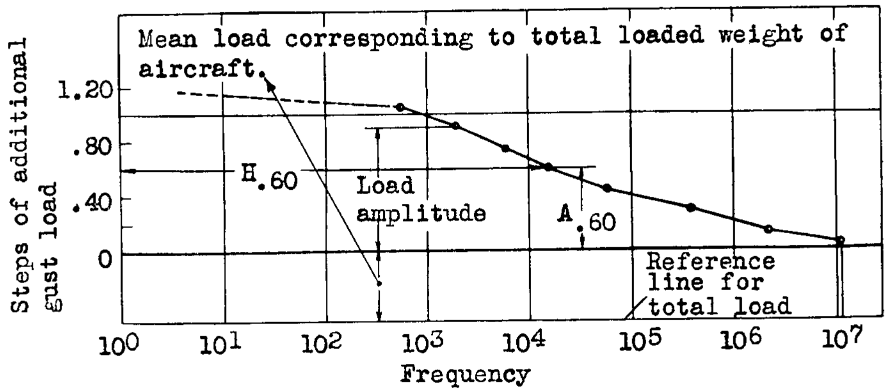


Figure 1.- Example of a sum-curve of the gust loads. (Cf. reference 5.)
$H_{.60}$ = frequency of occurence of loads exceeding load step .60.
$A_{.60}$ = load amplitude amounting to load step .60.

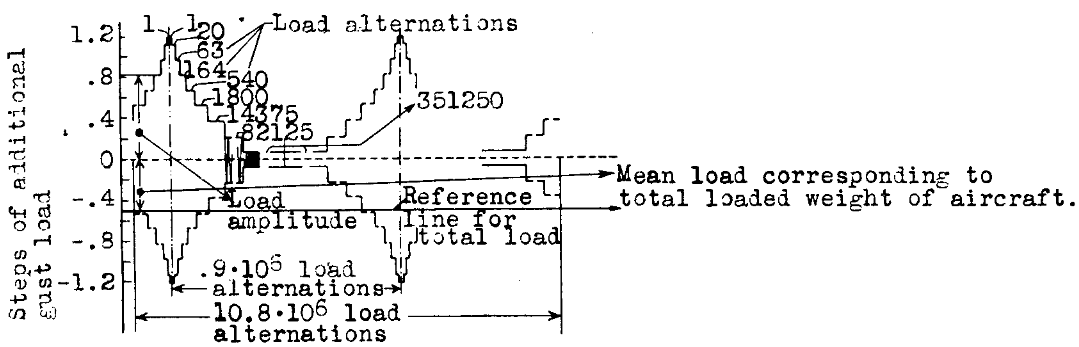


Figure 2.- Course of a strength test pertaining to flight statistics.

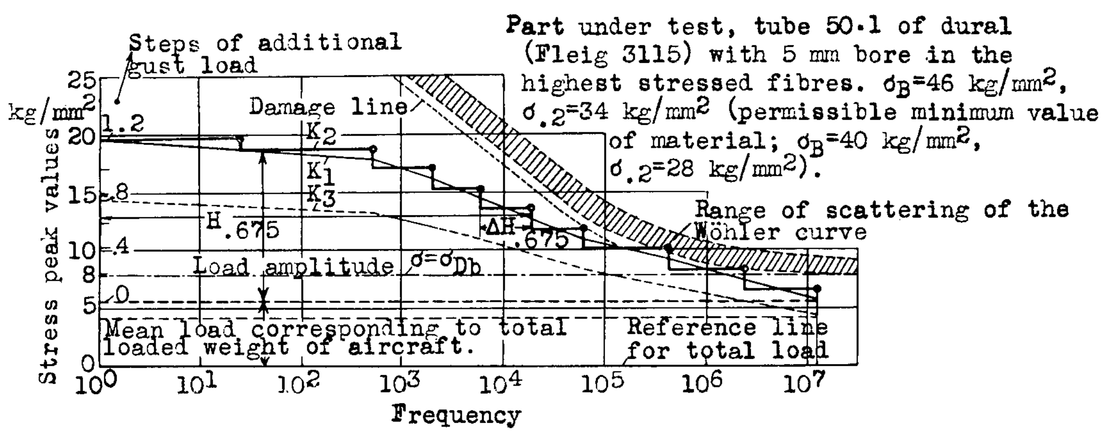


Figure 3.- Synoptic diagram of a strength test as interpreting flight statistics.
$k_1$ = given sum-curve of the operational loads. (Cf. figure 1.)
$k_2$ = sum-curve obtained from the tests.
$k_3$ = permissible sum-curve with a factor of safety 1.35.
$H_{.675}$ = frequency of exceeding step .675 of the gust load in the tests.
$\Delta H_{.675}$ = frequency of reaching step .675 of the gust load in the tests.

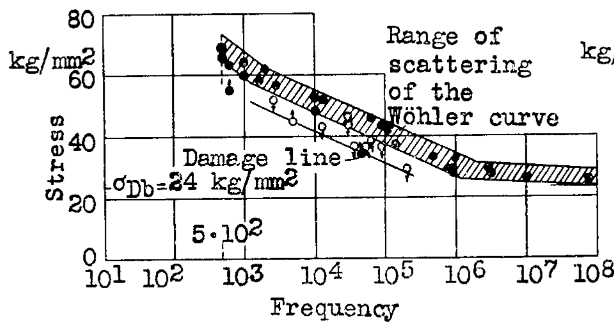


Figure 4.- Wöhler and damage curves for smooth steel tube 38·1 under alternate bending.
Material: Cr-Mo-steel (Flieg 1452.9) with $\sigma_B$=70 to 82 kg/mm² and $\sigma_{.2}$=63 to 76 kg/mm².

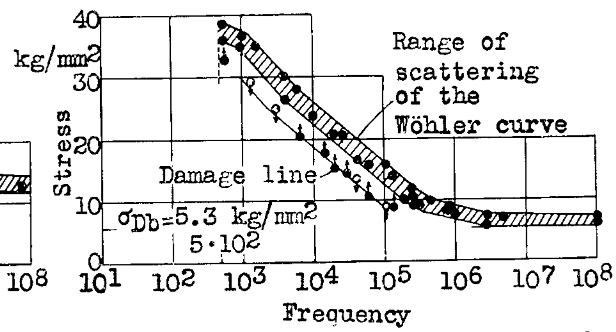


Figure 5.- Wöhler and damage curves for smooth duralumin tube 50·1 under alternate bending.
Material: Duralumin 681 (Flieg 3115) with $\sigma_B$=40 to 43 kg/mm² and $\sigma_{.2}$=28 to 32 kg/mm².

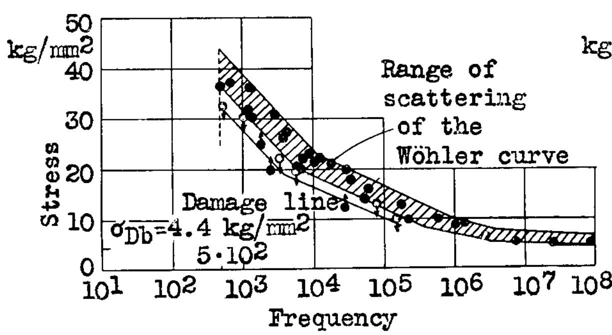


Figure 6.- Wöhler and damage curves for smooth hydronalium tube 50·1 under alternate bending.
Material: Hydronalium Hy 9 (Flieg 3315.7) with $\sigma_B$=38 to 39 kg/mm² and $\sigma_{.2}$=28 to 30 kg/mm².

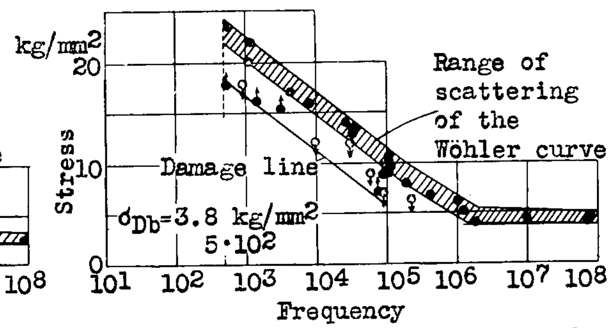


Figure 7.- Wöhler and damage curves for smooth electron tube 50·1 under alternate bending.
Material: Electron AZM (Flieg 3510.1) with $\sigma_B$=29 to 30 kg/mm² and $\sigma_{.2}$=16.5 to 17.5 kg/mm².

Figures 4 to 7.- Wöhler and damage curves for smooth tubes (alternate bending).

● Wöhler test.
Tests for recording the damage line.

Not yet fractured in the 2nd step with $2 \cdot 10^7$ load alternations.

Fractured already in step 2 before reaching $2 \cdot 10^7$ load alternations.

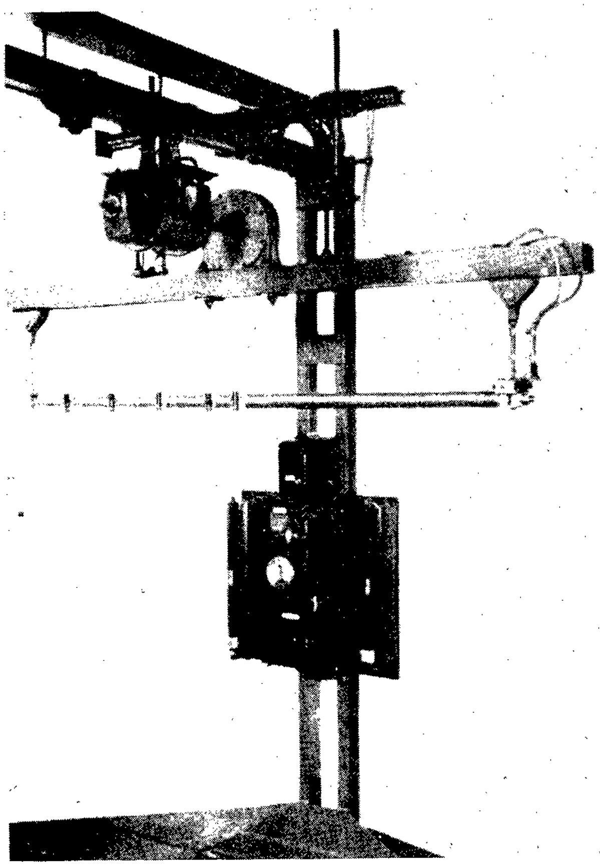

Figure 8.- DVL bending oscillation test machine for tests with a large number of load alternations.

The part under test (tube) is suspended from a flexibly mounted carrier and is set in oscillation by a rotating flywheel which is fixed to the carrier. As the rpm of the flywheel is made by a suitable mechanism to approximate the natural oscillation frequency of the part, the oscillation stresses of the latter can be stepped up or down arbitrarily. Their value is calculated from the amplitudes of the part. Constant amplitude values are obtained with the aid of a Schenck regulating apparatus.

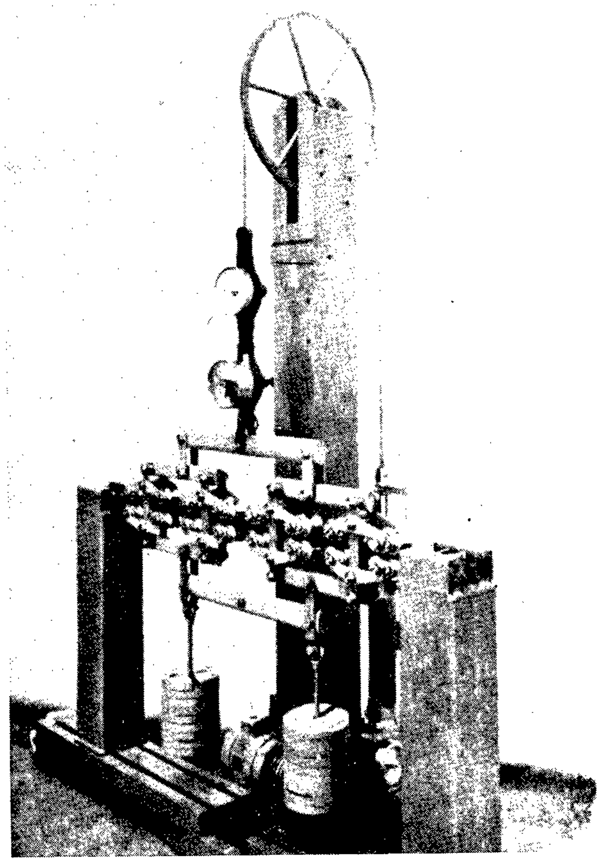

Figure 9.- DVL alternating winch for tests with a small number of load alternations.

The part under test (tube) is loaded through a suitable system of levers in one direction by weights and in the other direction by a screw spindle. The latter is driven by a reversing motor. On reaching the upper and lower load limits, the motion of the spindle is reversed by means of a contact dynamometer.